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EVOLUTION OF ULTRAHIGH-STRENGTH, HARDENABLE STEELS FOR SOLID-PROPELLANT ROCKET-MOTOR CASES

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EVOLUTION OF ULTRAHIGH-STRENGTH, HARDENABLE STEELS FOR SOLID-PROPELLANT ROCKET-MOTOR CASES

by

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to

OFFICE OF THE DIRECTOR OF DEFENSE
RESEARCH AND ENGINEERING

DEFENSE METALS INFORMATION CENTER
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EVOLUTION OF ULTRAHIGH-STRENGTH, HARDENABLE STEELS FOR SOLID-PROPELLANT ROCKET-MOTOR CASES

SUMMARY

This report discusses the evolution of the current roster of special steels which are used or are being considered for use in solid-propellant rocket cases, and shows their relationship to the older, more familiar steels. The evolution is traced from AISI 4130, through AISI 4340 and its modifications, and includes the 5Cr-Mo-V steels (hot-work die steels).

The discussion covers the influence of composition on performance and properties, response to tempering and the effects of tempering, and the differences and similarities among the steels. Also included are comments on such matters as fabrication, welding, heat treating, notch sensitivity, decarburization, high-temperature properties, and the benefits of vacuum melting.

The information in this report was obtained from the Defense Metals Information Center files at Battelle Memorial Institute and from other published literature.

INTRODUCTION

For numerous reasons, solid-propellant rocket-motor cases are constructed from moderately thin sheet metal. Considerations of availability, price, mechanical properties, and technical background make steel a favored material from which to construct these cases. However, stringent strength-to-weight requirements demand the utmost in strength and reliability from steel. Thus, it has become necessary to develop steels which can be used satisfactorily in thin sections at extremely high strength levels. Concomitantly, requirements with respect to all mechanical properties, surface stability, fabricability, and dimensional tolerances have become extremely exacting.

In order to meet these exacting requirements, many steels have been tested and evaluated. In addition, many proprietary steels, some with unfamiliar trade names, have been introduced into the technology of rockets and missiles. The combination of a special name and a special heat treatment may seem to set a certain steel apart as being a new or different material. Usually, however, these steels fall into a known class and actually are modifications of the older or more basic members of that class. The purpose of the modifications, and corresponding alterations in fabrication methods and heat treating procedures, is to provide materials particularly suited to the intended application. It is the intention in this report to describe how and why the high-strength steels presently used were evolved for solid-propellant rocket-casing application and to show their relationship to the more familiar steels.

TYPES OF STEEL IN USE OR UNDER CONSIDERATION

General Comments

The development of ever higher strength in steels has long been the goal of much research in ferrous metallurgy. Through the years, especially because of the persistent demands of the aircraft and missile industries, the strength level of steel has been raised progressively. Currently, for the larger solid-propellant rocket-motor cases, steels with strength-to-weight ratios in the order of 1,000,000 are desired (i.e., some 280,000-psi tensile strength). The primary means of increasing strength in steel has been to increase the alloy content and to lower the tempering temperature after quenching.

Most of the steels which are being used, or are being investigated for use, in present-day missiles can be divided into two major groups: the low-alloy engineering steels and the Cr-Mo-V hot-work die steels

(H-11 and H-13 types). The low-alloy engineering steels can be further subdivided into chromium-molybdenum (AISI 4100 series) and chromium-nickel-molybdenum (AISI 4300 series) types. Figure 1 shows a classification of typical steels in the three families. At the top of each list in the figure is a typical standard AISI steel in the family, while a number of proprietary steels and modifications are listed below.

The steels listed in Figure 1 have several similarities. High strength is achieved in all of them by heating to temperatures where the austenite phase is stable, cooling so as to transform the austenite to martensite, and tempering the martensitic structure to the desired hardness. All are susceptible to decarburization during fabrication and heat treatment. Although the hot-work die steels are slightly more corrosion resistant than are the low-alloy engineering steels, they, too, must be protected from their environment during shipment and storage after fabrication. Hydrogen embrittlement is a possibility to be considered in all heat-treated steels that have been pickled or plated. As the strength levels are increased, these steels all become increasingly notch sensitive.

Cr-Mo	Cr-Ni-Mo	5Cr-Mo-V Hot-Work Die Steels
Cr: 0.50-0.90	Cr: 0.50-0.80	Cr: 5.00
Mo: 0.12-0.20	Ni: 1.80	Mo: 1.50
	Mo: 0.25	V: 0.40-1.00
Typical Steels and Modifications	**Typical Steels and Modifications**	**Typical Steels and Modifications**
AISI 4130	AISI 4340	H-11
AISI 4140 (Mod.)	AMS 6434	H-13
17-22-AS	D-6-AC	Crucible 56 (Peerless 56)
Airsteel X-200	300-M	Crucible 218
UHS-260	USS Strux	Potomac A
UCX-2	Super Tricent	Potomac M
MBMC No. 1	HY-Tuf	Vascojet 1000
		Unimach I
		Unimach II
		Dynaflex

FIGURE 1. STEELS USED IN SOLID-PROPELLANT ROCKET-MOTOR CASES, CLASSIFIED BY COMPOSITION TYPE

Martensite is the hardest and strongest transformation product of austenite. Its strength is to a major extent dependent on its carbon content, as is suggested in Figure 2. As a consequence, the maximum strength and hardness attainable in a steel so heat treated as to have a completely martensitic structure is equally dependent on the carbon content. The addition of alloying elements has a minor effect on the ultimate strength but may change the yield-to-ultimate strength ratio, the depth of hardening on quenching (hardenability), the tendency toward decarburization, the resistance to softening on tempering, and the notch sensitivity. The alloying elements commonly added to steel and a summary of their effects are listed in Table 1. All of the elements listed, with the exception of cobalt, increase hardenability; that is, they promote strengthening throughout the cross section of larger parts. Molybdenum and chromium also contribute to strength at elevated temperatures. Since all the steels used at high-strength levels are tempered after hardening, a brief discussion of the reasons for tempering and of the effects of tempering on the structure and properties of the steel should help to clarify the function of alloying in martensitic steels.

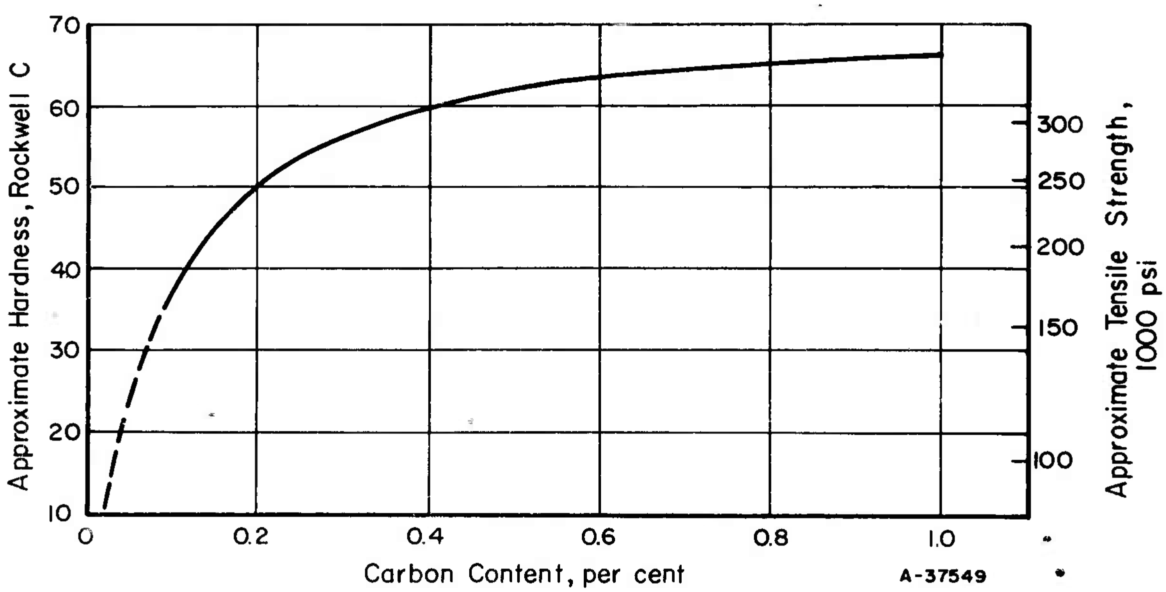

FIGURE 2. THE MAXIMUM OBTAINABLE HARDNESS OF UNTEMPERED, FULLY MARTENSITIC STEEL AS A FUNCTION OF CARBON CONTENT

The relationships among carbon content, hardness, and tensile strength are approximations.(1)*

The hardness of a fully martensitic steel is virtually at a maximum when it is in the untempered condition. However, the maximum hardness and strength obtainable is seldom used in a part, because the separation

*References are listed on page 37.

TABLE 1. SOME SPECIFIC EFFECTS OF ALLOYING ELEMENTS ON STEEL[1,2]

(On the Basis of Weight Percentage)

Element	Influence on Hardenability	Carbide-Forming Tendencies	Action During Tempering	Other Functions
Chromium	Increases strongly	Greater than Mn, less than W	Sustains strength by secondary hardening; Mildly sustains hardness by solid-solution strengthening	Increases corrosion and oxidation resistance; contributes some high-temperature strength and abrasion resistance in high-carbon compositions
Cobalt	Decreases	Less than Fe	Sustains hardness by solid-solution strengthening	Resists softening at high temperatures when dissolved in ferrite; hardens ferrite
Manganese	Increases very strongly (Second only to C)	Greater than Fe, less than Cr	Sustains hardness more effectively than Si in solid solution	Forms harmless sulfides favorable to machinability; produces a high-carbon austenitic steel; increases strength of ferrite but reduces plasticity
Molybdenum	Increases strongly	Strong; greater than Cr and W	Opposes softening strongly by secondary hardening	Raises austenitic coarsening temperature; raises high-temperature strength and creep resistance, and enhances corrosion resistance of stainless steel
Nickel	Increases mildly (less than Si)	Negative (graphitizes)	Very little effect in small percentages	Renders high-chromium steels austenitic; promotes low-temperature toughness in ferritic-pearlitic steels
Silicon	Increases moderately	Negative (graphitizes)	Sustains hardness by solid solution	Aids in regularity of crystallization of low-carbon steels and raises electrical resistivity; increases strength in quenched and tempered steels; a general-purpose deoxidizer
Titanium	Probably increases strongly as dissolved	Greatest	Some secondary hardening	Produces carbides which reduce martensitic hardness and hardenability of medium-chromium steels; prevents intergranular deterioration in austenitic stainless steels; used as a deoxidizer

TABLE 1. (Continued)

Element	Influence on Hardenability	Carbide-Forming Tendencies	Action During Tempering	Other Functions
Tungsten	Increases moderately in small amounts	Strong	Sustains strength by secondary hardening	Formation of hard, abrasion-resistant carbides in tools, together with development of high-temperature hardness in quenched and tempered steels; generally similar to molybdenum
Vanadium	Increases very strongly up to 0.05%V; decreases with more than 0.17%V	Very strong	Maximum secondary hardening effect	Elevates coarsening temperature of austenite; promotes secondary hardening

between the flow (yield) and fracture (ultimate) stresses is small and, hence, the ductility and resistance to brittle failure are low. Tempering serves to increase the toughness and ductility of the steel, although strength and hardness are sacrificed. Generally, the higher the tempering temperature, the greater will be the ductility but the lower will be the strength and hardness of a given steel.

When most medium-carbon steels are quenched to form martensite and then tempered at successively higher temperatures, the toughness (as measured by the notched-bar impact test) increases progressively up to a tempering temperature of about 400 F. However, on tempering at temperatures in the range of about 400 to 700 F, the toughness decreases, passes through a minimum, and then increases again. This is illustrated in Figure 3 for AISI 4340, a typical aircraft steel. The loss in toughness of martensitic steels at high hardness levels (relatively low tempering temperatures) is known as "500 F embrittlement" or "tempered martensite brittleness". It is this embrittlement that long delayed the use of alloy steels for structural applications at strength levels much above 200,000 psi.

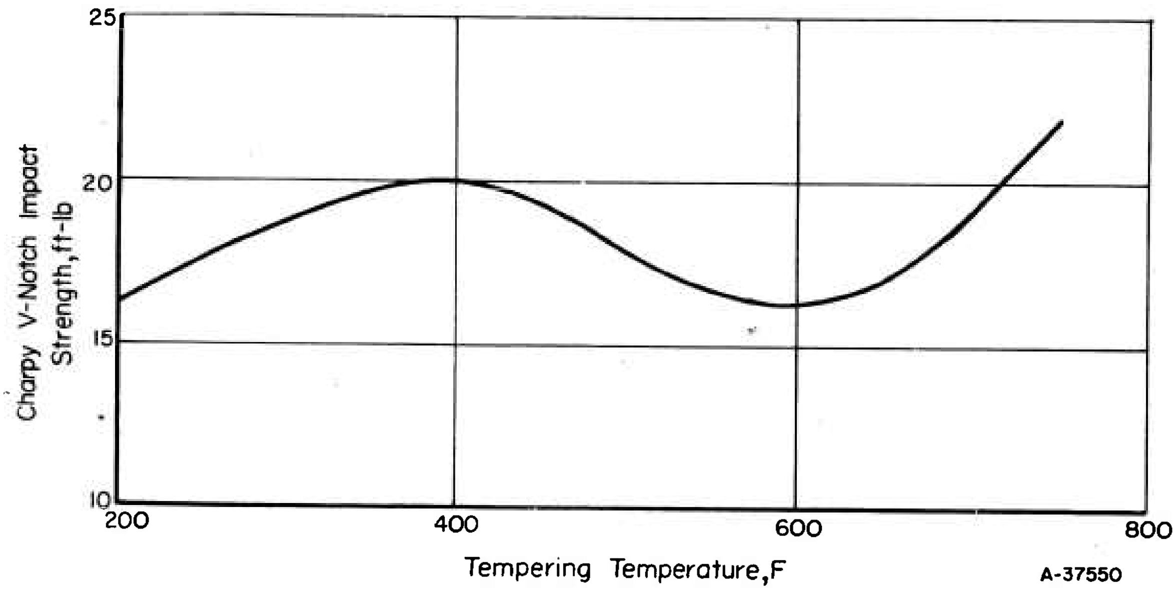

FIGURE 3. THE EFFECT OF TEMPERING TEMPERATURE ON THE IMPACT STRENGTH OF AISI 4340, A TYPICAL AIRCRAFT STEEL

When a steel part is cooled very rapidly after it has been austenitized, as it is in quenching, residual stresses of considerable magnitude are introduced, even in the absence of a transformation reaction. This condition arises because, during very rapid cooling, the surface cools most rapidly and a large temperature differential exists between the surface and the center of the part. In addition, a volume expansion is

associated with the formation of martensite. This expansion introduces additional stresses into the part. These residual stresses arising from quenching and from transformation lower the external load that a part can carry. Therefore, an important function of tempering is to relieve these internal stresses.

The magnitude of the residual stresses is reduced by the addition of alloying elements which increase the hardenability and make it possible to obtain a fully martensitic structure with a less drastic quench. The slower cooling from the austenitizing temperature (less drastic quench) allows some stress relief on cooling. In turn, the lower residual stresses allow a lower tempering temperature to be used to obtain a tough steel.

The increase in toughness and the softening that a steel undergoes on tempering result from relief of stresses, from crystallization, and from coalescence and spheroidization of carbides. These changes result in a microstructure of increased plasticity. Most of the elements added to steel will slow up the phenomenon of carbide formation and coalescence, and thus retard softening during tempering as is shown in Table 1. The carbide-forming elements which are dissolved in the steel will, on tempering at appropriate temperatures, form alloy carbides which, when precipitated in the steel, produce some hardening. This "secondary hardening" may either retard softening on tempering or, at high tempering temperatures, actually cause an increase in hardness.

Some of the most widely used modifications of the high-strength steels have been the high-silicon alloy steels with silicon contents up to 2.00 per cent. The addition of silicon to hardenable steels has been shown to retard the softening which occurs on tempering.(1,3) This is illustrated in Figure 4. Also, increasing the silicon increases the tensile strength, with no attendant loss in ductility. The minimum, or plateau, in impact strength of alloy steels, usually shown in the temperature range from a little over 400 to approximately 700 F (500 F embrittlement), is shifted to higher temperatures by additions of silicon.(4)

Low-Alloy Hardenable Steels

The low-alloy hardenable steels have been used for high-strength applications in the aircraft and ground-transportation industries for years. An early use of these steels in the aircraft industry was for landing-gear components heat treated to tensile strengths of the order of 180,000 psi. Other uses included bolts, pins, fittings, and engine mounts.(5,6,7) As mentioned previously, these steels can be subdivided into two groups, the chromium-molybdenum and the chromium-nickel-molybdenum steels.

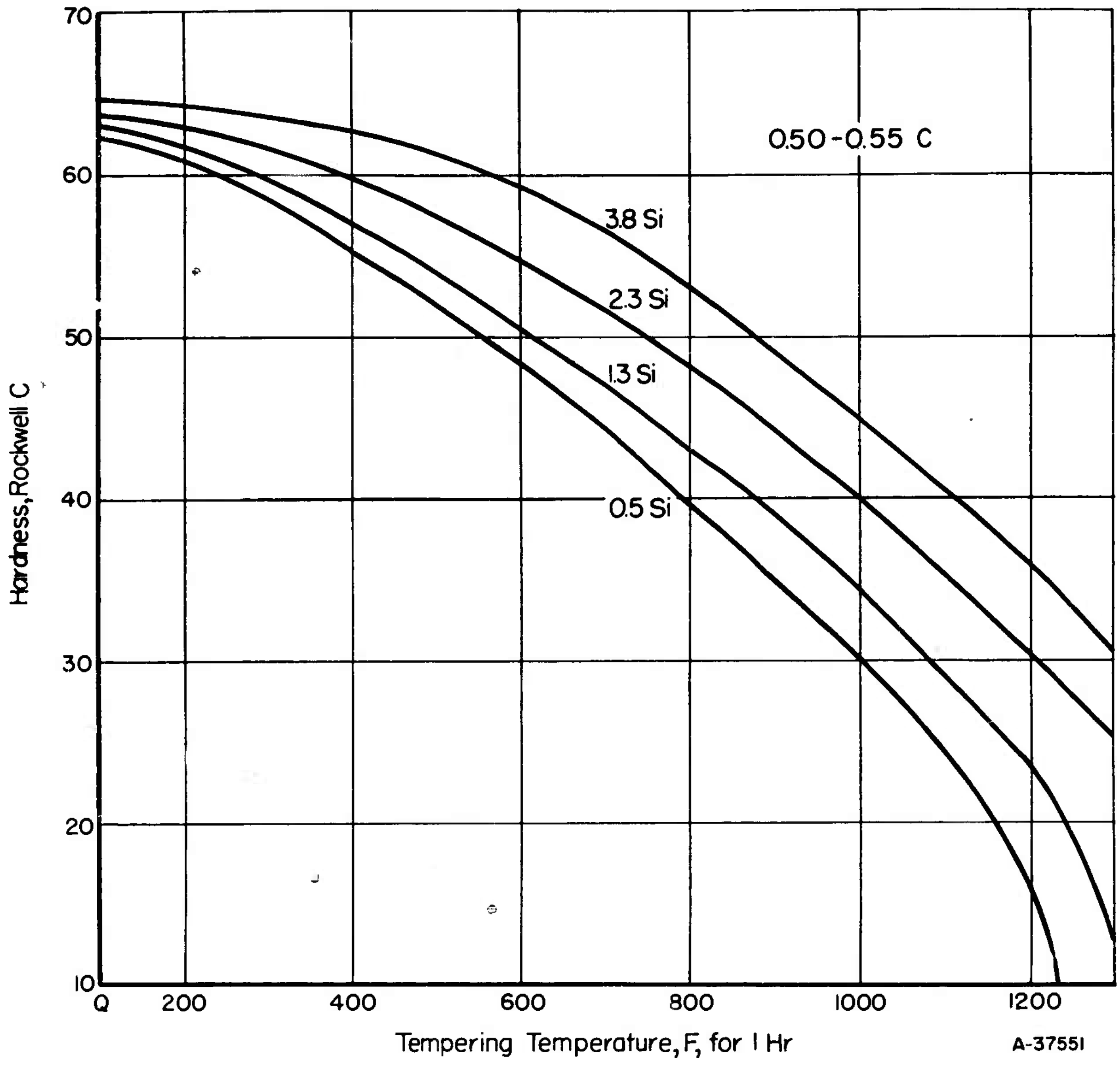

FIGURE 4. THE SOFTENING, WITH INCREASING TEMPERING TEMPERATURE, OF QUENCHED 0.50 - 0.55 PER CENT CARBON STEEL AS INFLUENCED BY SILICON CONTENT[1]

Chromium-Molybdenum Steels

Steels in this category that are used or that are under consideration for use in the missile industry for solid-propellant rocket-motor cases are listed in Table 2; chemical compositions are included. The first steel in this list is AISI 4130, which can be considered to be the base steel from which the others evolved. When working stresses in welded aircraft parts reached a point where plain-carbon steels were no longer satisfactory, AISI 4130, a mildly air-hardening steel, was developed to meet the new requirements. Increased hardenability over that of its plain-carbon counterpart is obtained from the chromium and molybdenum additions. This steel is characterized by excellent strength-to-weight ratio and outstanding weldability, and has been a most important material in aircraft structural assemblies. In addition, it has been used for other engineering construction involving high stresses, particularly where extensive welding and medium hardenability are required.

TABLE 2. TYPICAL CHROMIUM-MOLYBDENUM HARDENABLE STEELS USED IN SOLID-PROPELLANT ROCKET-MOTOR CASES

Designation	Composition, per cent						
	C	Mn	Si	Cr	Mo	V	Others
AISI 4130	0.28-0.33	0.40-0.60	0.20-0.35	0.80-1.10	0.15-0.25	--	--
AISI 4140	0.38-0.43	0.75-1.00	0.20-0.35	0.80-1.10	0.15-0.25	--	--
17-22-AS	0.28-0.33	0.45-0.65	0.55-0.75	1.00-1.50	0.40-0.60	0.20-0.30	--
UCX-2[(a)]	0.39	0.70	1.00	1.10	0.25	0.15	1.00Co
MBMC No. 1	0.42-0.46	0.70-0.90	1.50-1.70	0.60-0.90	--	0.10 Min	--
Airsteel X-200	0.41-0.46	0.75-1.00	1.40-1.75	1.90-2.25	0.45-0.60	0.03-0.08	--

(a) This is an experimental steel. The analysis shown is a typical analysis listed in the Universal Cyclops brochure on UCX-2.

The second steel listed in Table 2, AISI 4140, is a steel which has, by virtue of its higher carbon and manganese contents, higher strength and higher hardenability than does AISI 4130. However, AISI 4140 is somewhat less readily welded because of its higher carbon content. This steel has been used for applications which require heavier sections, but in which the part can be preheated and postheated if welding is necessary. It is included in the list of steels to illustrate the transition from the typical lean-alloy composition of an AISI 4130 steel to the more highly alloyed, higher carbon steels used in rocket-motor cases.

Properties developed in AISI 4130 by simple normalizing treatments or by normalizing and tempering have been adequate for many past applications. However, only full heat treatment, consisting of quenching and tempering, will develop in this steel the strengths required for solid-propellant rocket applications.

The wide use of this material in the aircraft industry and the resultant familiarity with its characteristics made AISI 4130 steel a natural early selection for use in high-strength rocket-motor cases. The other, less familiar, chromium-molybdenum steels listed in Table 2, with the exception of 17-22-AS, were evolved later, specifically for use in the rocket and missile industry. The notable differences between the composition of AISI 4130 and those of the special steels are the higher carbon and silicon contents in the latter and the addition of vanadium or, in UCX-2, both vanadium and cobalt to the modified alloys. The higher contents of carbon, chromium, and molybdenum increase the strength and the hardenability attainable on quenching, while the additions of silicon and cobalt serve primarily to retard softening on tempering. Chromium, molybdenum, and vanadium also contribute to resistance to softening on tempering, but they are particularly effective at high tempering temperatures where the formation of alloy carbides results in secondary hardening. Vanadium is also effective in maintaining a fine grain size in the steel. These are the advantages which these special steels offer over AISI 4130. They are shown in Figure 5 which illustrates the strengths obtained and the retarding of softening and weakening on tempering observed in the steels listed in Table 2 (with AISI 4140 omitted).

The addition of silicon to the alloys listed has another beneficial effect during tempering. The occurrence of brittleness on tempering in the so-called 500 F embrittlement range is shifted to a higher temperature.

Steel 17-22-AS was developed by Timken for its resistance to thermal cracking, heat checking, and shock at high hardness levels. It also has good resistance to hot upsetting under rapidly applied stresses up to 1000 F. This steel relies on a normalizing treatment, rather than on quenching, to achieve high strengths. As a result, its creep resistance and rupture resistance are greater than those of other low-alloy hardenable steels and are almost as good as those of the hot-work die steels. Hot-bolting and sheet for jet-engine compressor cases are typical aircraft uses. This steel had been used for flanges, fittings, brake disks, and hot dies prior to its consideration for use in aircraft and rockets.

Of the other three steels listed in Table 2, which were developed especially for rocket and missile applications, UCX-2 (cobalt-modified 4137) was developed at Mellon Institute as Composition MX-2[9,12], designed to be used at yield strengths greater than 230,000 psi. The cobalt addition retards tempering action, as does silicon. This steel is now produced by Universal-Cyclops as UCX-2. MBMC No. 1 (a silicon-modified steel) was proposed as a missile steel by the Missile Boosters Materials Committee[10]. It was presented as being a suitable sheet material for use at yield-strength levels in excess of 200,000 psi. Airsteel X-200 also is a silicon-modified steel, but with increased chromium[11]. This combination helps retard softening on tempering more than does silicon alone. The improved resistance to softening on tempering is illustrated by comparing the

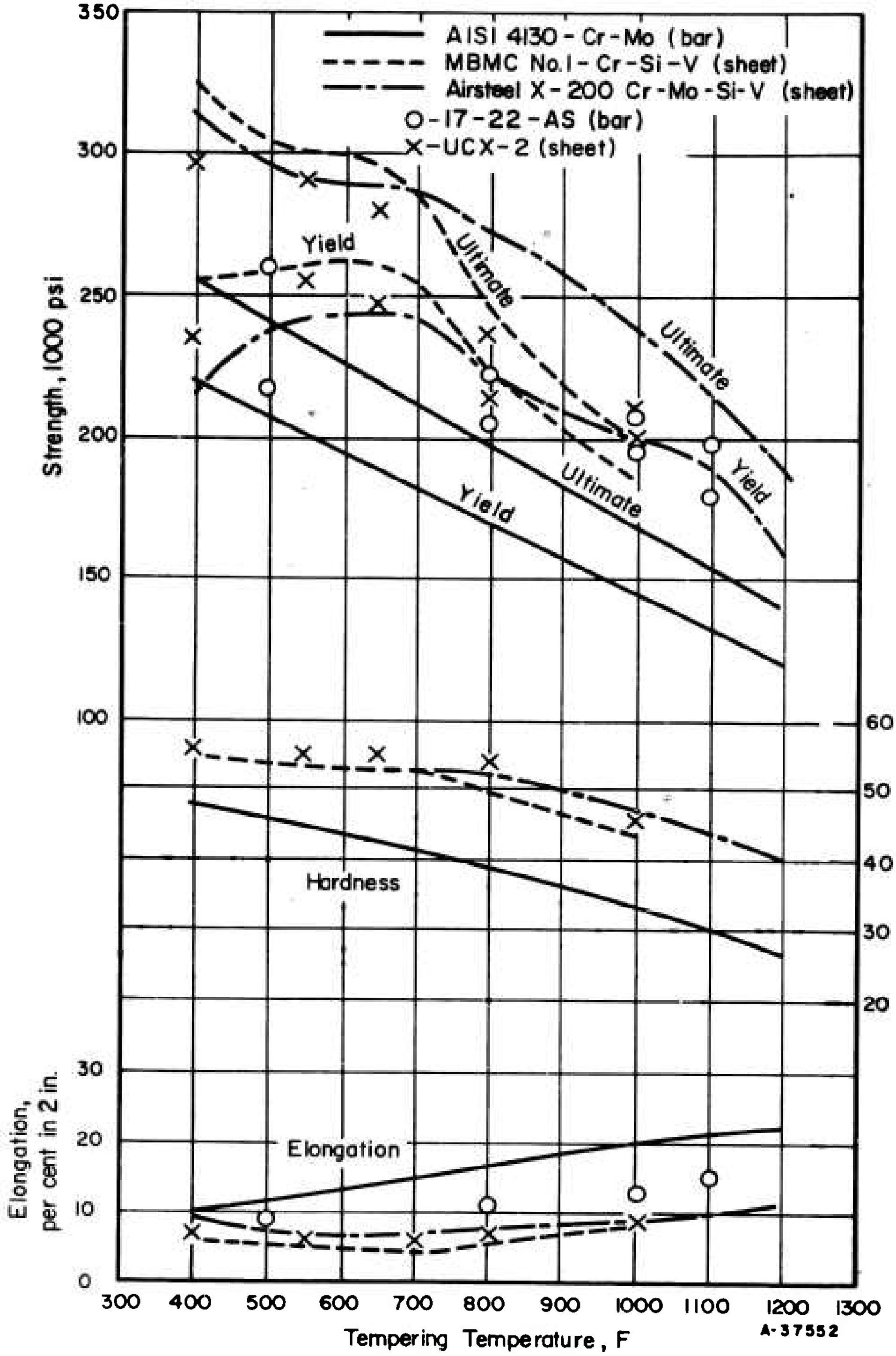

FIGURE 5. EFFECTS OF VARIOUS TEMPERING TEMPERATURES ON THE PROPERTIES OF AISI 4130 AND FOUR MODIFICATIONS OF THIS CHROMIUM-MOLYBDENUM STEEL(8-11)

curves in Figure 5 for MBMC No. 1 (0.60-0.90 chromium, 1.50-1.70 silicon) and Airsteel X-200 (1.90-2.25 chromium, 1.40-1.75 silicon). Airsteel X-200 is air hardening in thin sections. It was developed for the rocket and missile industry by the United States Steel Corporation.

The retarding of softening on tempering in these modifications of AISI allows higher tempering temperatures to be used and, thereby, greater relief of residual stresses is obtained. Typical heat treatments for these steels are described later.

Chromium-Nickel-Molybdenum Steels

The first steel developed in this group was AISI 4340. It was designed for applications requiring higher strength or where heavier sections are to be hardened throughout than would be feasible with AISI 4130. The increased strength of this steel arises largely from increased carbon content, while increased hardenability stems from increases in manganese and molybdenum and from the addition of nickel. This steel, too, has been used for many years in the aircraft industry in landing gears and other critical parts. At present, it is being used for parts heat treated to tensile strengths up to 280,000 psi[13,14]. Because of its widespread use and industry's familiarity with this steel, it has become the standard high-strength steel. The properties of AISI 4340 are used as a standard of comparison for other low-alloy hardenable steels during their development or as a criterion for materials selection.

The chemical composition of AISI 4340 and modifications of this analysis now in use or under consideration for use in solid-propellant rocket-motor cases are listed in Table 3.

Of the steels in this group, AMS 6434[15] has been used more widely than any other for fabrication of solid-propellant rocket-motor cases. This steel is AISI 4340 with lower carbon for better weldability, with the molybdenum increased to compensate for the loss in hardenability caused by the lower carbon content, and with vanadium added as a grain refiner. It is used at heat-treated yield-strength levels of 185,000 to 210,000 psi. Resistance to crack-propagation drops noticeably at higher strength levels.

D-6-AC[16] is a consumable-electrode-melted material of the same composition as Ladish D-6-A, an air-melted steel which has been used for twenty years in low-alloy die blocks. The vacuum-melted material was evolved to meet the higher quality standards of rocket and missile applications. D-6-AC is noted for its cleanliness, uniform response to heat treatment, and excellent transverse ductility. Normally, it is used in the 200,000-psi yield-strength range with a hardness of 46 to 47 Rockwell C and an elongation of about 10 per cent.

TABLE 3. TYPICAL CHROMIUM-NICKEL-MOLYBDENUM HARDENABLE STEELS AND MODIFICATIONS USED IN SOLID-PROPELLANT ROCKET-MOTOR CASES

Designation	Composition, per cent							
	C	Mn	Si	Cr	Ni	Mo	V	Others
AISI 4340	0.38-0.43	0.60-0.80	0.20-0.35	0.70-0.90	1.65-2.00	0.20-0.30	--	--
AMS 6434	0.31-0.38	0.60-0.80	0.20-0.35	0.65-0.90	1.65-2.00	0.30-0.40	0.17-0.23	--
Ladish D-6-A	0.42-0.48	0.60-0.90	0.15-0.30	0.90-1.20	0.40-0.70	0.90-1.10	0.05-0.10	--
300-M (Tricent)	0.41-0.46	0.65-0.90	1.45-1.80	0.70-0.95	1.65-2.00	0.30-0.45	0.05 (min)	--
HY-Tuf	0.25	1.30	1.50	--	1.80	0.40	--	--
USS Strux	0.40-0.47	0.75-1.00	0.50-0.80	0.80-1.05	0.60-0.90	0.45-0.60	0.01 (min)	0.0005 B (min)

The other three steels in this group were developed specifically for the aircraft industry for parts which require a combination of high strength and toughness, such as landing gears. All three have been in existence for a number of years. HY-Tuf was patented in 1948, while USS Strux and 300-M were introduced in 1952 and 1953, respectively.

The mechanical properties obtained on tempering these steels at various temperatures are illustrated in Figure 6. Comparison of the curves in Figure 6 and the compositions in Table 3 shows that unless the alloy content is increased considerably, AISI 4340 and minor modifications of this steel, such as AMS 6434 or D-6-AC, must be tempered below about 750 F to achieve yield strengths much over 200,000 psi. However, tempering in the range from a little above 400 F to approximately 700 F is not practicable for AISI 4340 because of "500 F embrittlement".

The last steel in Table 3, USS Strux[17], is a high-carbon modification which was designed to utilize the hardenability effects of boron. The addition of small amounts of boron allows heavy sections to be hardened throughout on quenching. The higher carbon content increases the strength of this steel beyond that of AISI 4340, and the increased chromium, molybdenum, and vanadium contents allow tempering in the 500 F range. For optimum notch toughness at ultrahigh strength levels, this steel should not be tempered above 600 F.

Lowering the tempering temperature of AISI 4340 steel to about 400 F avoids the 500 F embrittlement range. However, to secure tensile strengths between 200,000 and 270,000 psi with AISI 4340 requires tempering between 500 and 280 F. Therefore, since the upper part of this tempering range is undesirable, new compositions for use in the intermediate strength range had to be designed which could be safely tempered in this danger zone.

AMS 6434 was developed from AISI 4340 by lowering the carbon content, increasing the molybdenum, and adding a small percentage of vanadium. As a result of these modifications, this steel shows better Charpy impact values than does AISI 4340, both at 230,000- and at 250,000-psi tensile strength. The same result is accomplished in Ladish D-6-A by increasing the manganese and molybdenum and adding a small amount of vanadium.

The first tailored ultrahigh-strength steel, HY-Tuf[18], took advantage of the unusual characteristics imparted by silicon to quenched-and-tempered steels. As shown previously, increasing the silicon tends to retard softening on tempering, especially at tempering temperatures above 400 F (see Figure 4). Thus, a steel containing 1.5 to 2.0 per cent silicon can be tempered at around 600 F to provide hardness and strength equivalent to that of a similar steel of normal silicon content tempered at a much lower temperature. The higher tempering temperature allows more complete relief of residual quenching stresses with resultant improvement in

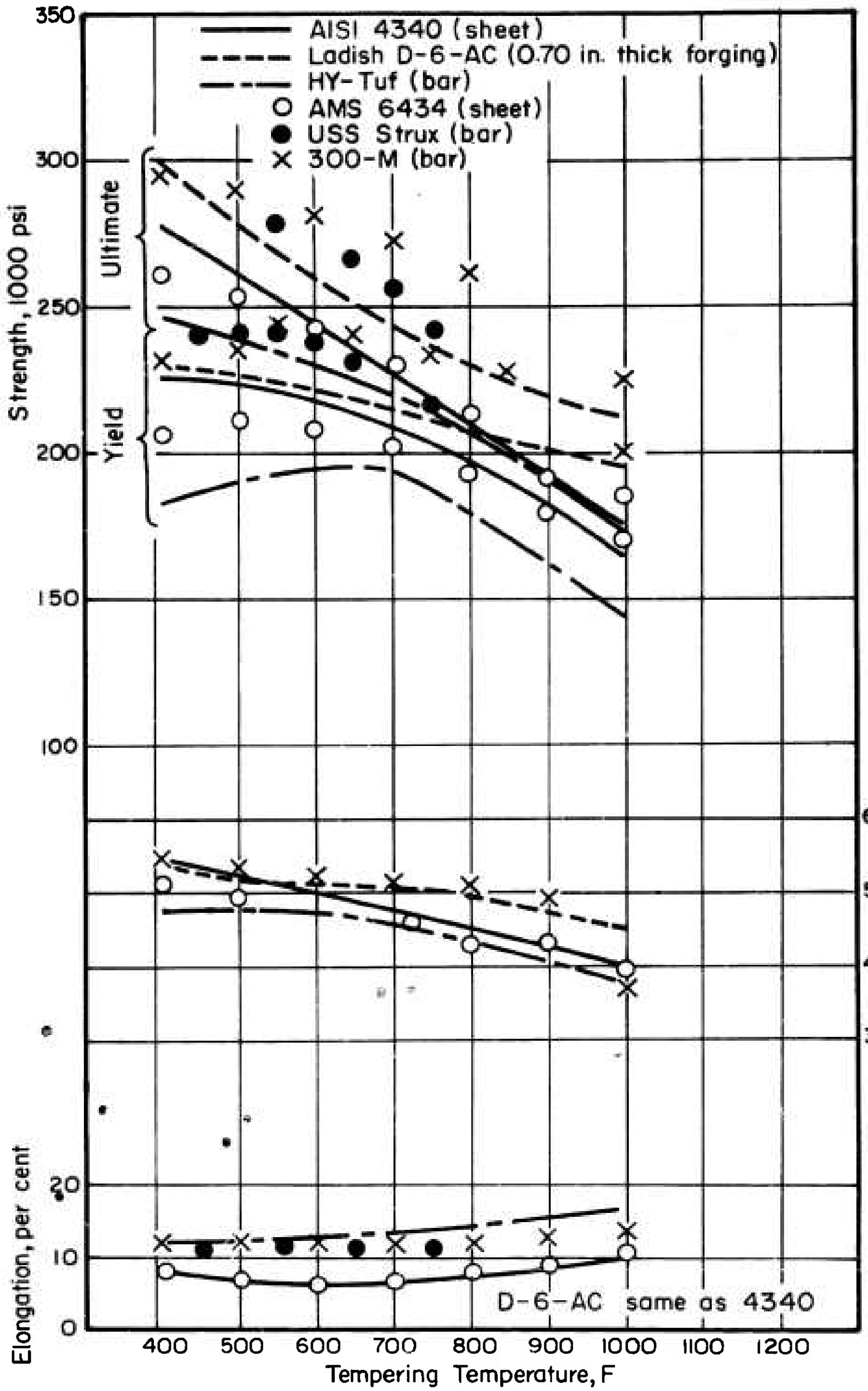

FIGURE 6. EFFECTS OF VARIOUS TEMPERING TEMPERATURES ON THE PROPERTIES OF AISI 4340 AND FIVE MODIFICATIONS OF THIS Cr-Mo-Ni STEEL[14-19]

yield strength and ductility. Also, silicon shifts the so-called 500 F embrittlement, or tempered martensite brittleness, to higher tempering temperatures. As a result, comparatively good notch toughness is obtained in high-silicon steels tempered in the range from 400 to 600 F. Both 300-M and HY-Tuf take advantage of these unique properties imparted by silicon.

Not only was 300-M[19,20] tailored specifically to avoid 500 F embrittlement and to take advantage of the resistance to tempering provided by its high silicon content, but the increased carbon content results in higher ultimate strengths. The effectiveness of silicon in overcoming the limitations on tempering in the range from just above 400 F to about 700 F is illustrated in Figure 7. This figure compares the V-notch Charpy impact strengths of AISI 4340 (0.20-0.35 silicon) and 300-M (1.45-1.80 silicon).

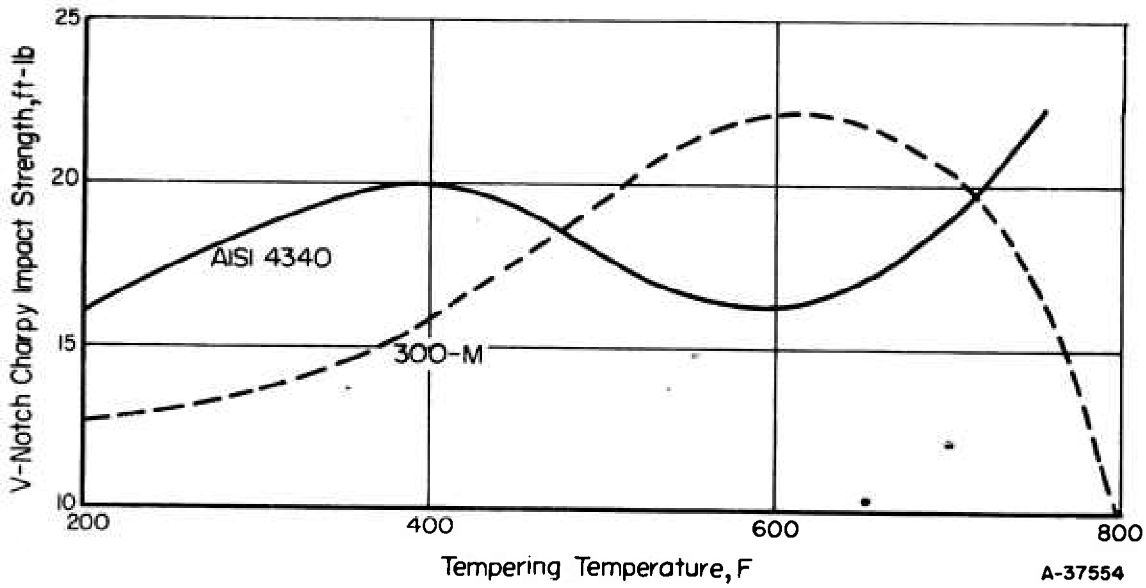

FIGURE 7. EFFECT OF TEMPERING TEMPERATURE ON THE IMPACT STRENGTH OF AISI 4340 AND 300-M (TRICENT)[14]

5Cr-Mo-V Steels

The 5Cr-Mo-V steels have been used for many years for tools requiring high strength and toughness at elevated temperatures. For about 25 years, a group of proprietary steels has been used in dies and fixtures that commonly experience temperatures near 1000 F. These steels are known as "hot-work tool steels", "hot-work die steels", or sometimes just "die steels". Consideration of these steels for missile requirements is based to a large extent on their comparatively high strength and high resistance to softening at service temperatures from room temperature to around 1000 F. Also, they have creep and stress-rupture values comparable to those of superalloys at 1000 F. Up to 1200 F, some of these steels have the highest strength-to-weight ratio of any commercial structural metal, because they can be heat treated to tensile strengths of from 260,000 to 300,000 psi at high tempering temperatures.(21) Another feature of these steels is greater stress relief, accomplished by tempering at relatively high temperatures, as compared with the low-alloy engineering steels. This is especially important in welded components, such as rocket-motor cases.

Because most of these steels were proprietary in a highly competitive field, no industrywide standards as to compositional or property limits were established. With the current interest in these steels, measures have been taken to standardize on an aircraft-quality H-11 type steel.(22) This steel has the designation "5Cr-Mo-V aircraft steel". The compositional limits of this steel are shown in Table 4, along with the compositions of standard H-11 and H-13 hot-work die steels and some of the proprietary steels considered for use in rocket-motor cases. As shown in Table 4, these steels contain relatively large amounts of alloying elements as compared with the low-alloy engineering steels. The high alloy content of these steels increases the hardenability so that fairly heavy sections can be hardened throughout by air cooling. This avoids some of the distortion inherent to quenching. The carbon content of 0.35 to 0.50 per cent is high enough to obtain high strength on quenching, but is not too high for adequate weldability. The 1 per cent silicon retards softening on tempering and increases strength and toughness. Chromium and molybdenum also help retard softening on tempering, as is shown in Figures 8 and 9. Vanadium, a strong carbide former, contributes strongly to the retardation of softening on tempering, if the carbide particles are dissolved on austenitizing. The increase in hardness and strength shown at the higher tempering temperatures is typical of the secondary hardening caused by these carbide-forming elements.

The superior ductility and toughness of these relatively high-alloy steels are a result of their heat treatment which produces a stable stress-free structure while avoiding most of the undesirable features of other high-strength steels. The extremely high hardenability allows these steels to be fully hardened by air cooling from austenitizing temperature.

TABLE 4. TYPICAL 5Cr-Mo-V STEELS CONSIDERED FOR USE IN ROCKET-MOTOR CASES

Designation	Composition, per cent					
	C	Mn	Si	Cr	Mo	V
5Cr-Mo-V aircraft steel	0.37-0.43	0.20-0.40	0.80-1.20	4.75-5.25	1.20-1.40	0.4-0.6
H-11	0.30-0.40	0.20-0.40	0.80-1.20	4.75-5.50	1.25-1.75	0.30-0.50
H-13	0.30-0.40	0.20-0.40	0.80-1.20	4.75-5.50	1.25-1.75	0.80-1.20
Vascojet 1000	0.40	0.30	0.90	5.00	1.30	0.50
Crucible 56	0.38-0.44	0.40-0.70	0.80-1.20	3.00-3.60	2.00-2.75	0.25-0.50
Crucible 218	0.40	0.40	1.05	5.00	1.35	0.50
Potomac A	0.40	0.30	0.90	5.00	1.30	0.50
Potomac M	0.40	0.30	1.00	5.00	1.00	1.00
Dynaflex	0.40	0.30	0.90	5.00	1.30	0.50
Unimach I (Thermold A)	0.35	0.45	1.00	5.00	1.40	0.45
Unimach II[a] (Thermold J)	0.50	0.40	1.10	5.00	1.40	1.00

(a) Plus 1.50 per cent nickel.

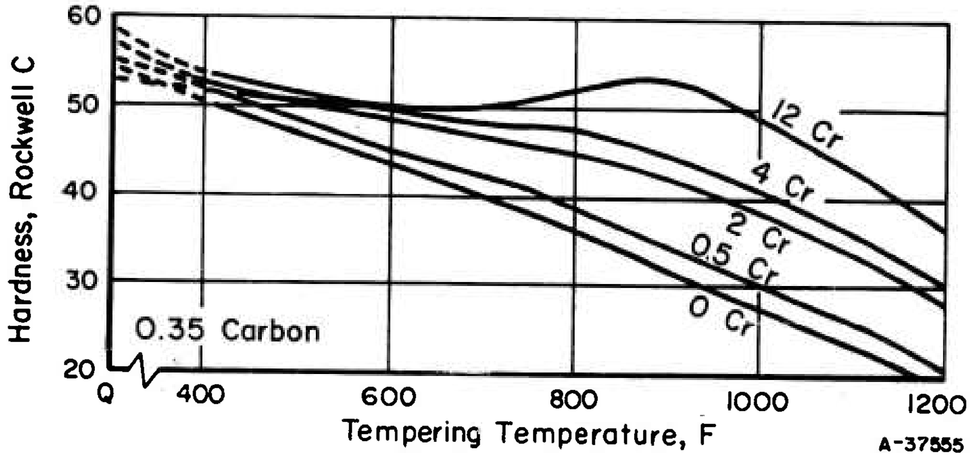

FIGURE 8. THE SOFTENING WITH INCREASED TEMPERING TEMPERATURE OF QUENCHED 0.35 PER CENT CARBON STEELS AS INFLUENCED BY CHROMIUM CONTENT(1)

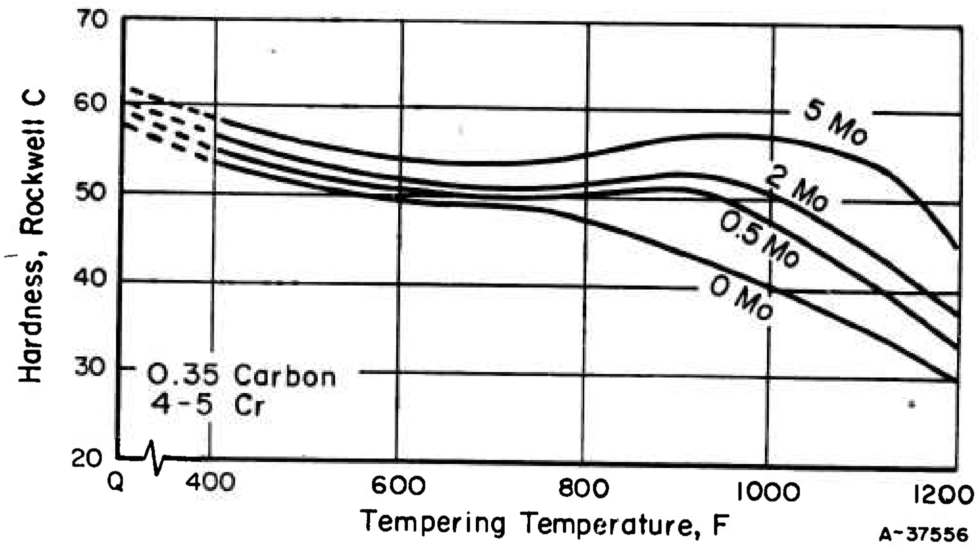

FIGURE 9. THE SOFTENING WITH INCREASING TEMPERING TEMPERATURE OF 4 TO 5 PER CENT CHROMIUM, 0.35 PER CENT CARBON STEELS AS INFLUENCED BY MOLYBDENUM CONTENT(1)

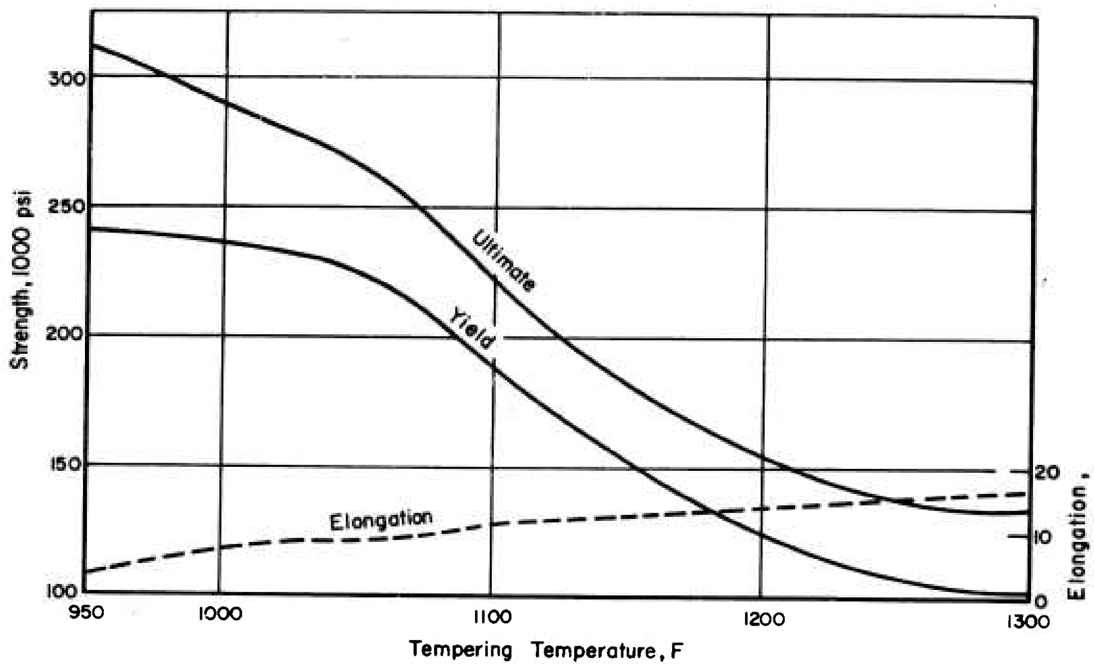

FIGURE 10. EFFECT OF TEMPERING TEMPERATURE ON THE PROPERTIES OF AN H-11 STEEL[22]

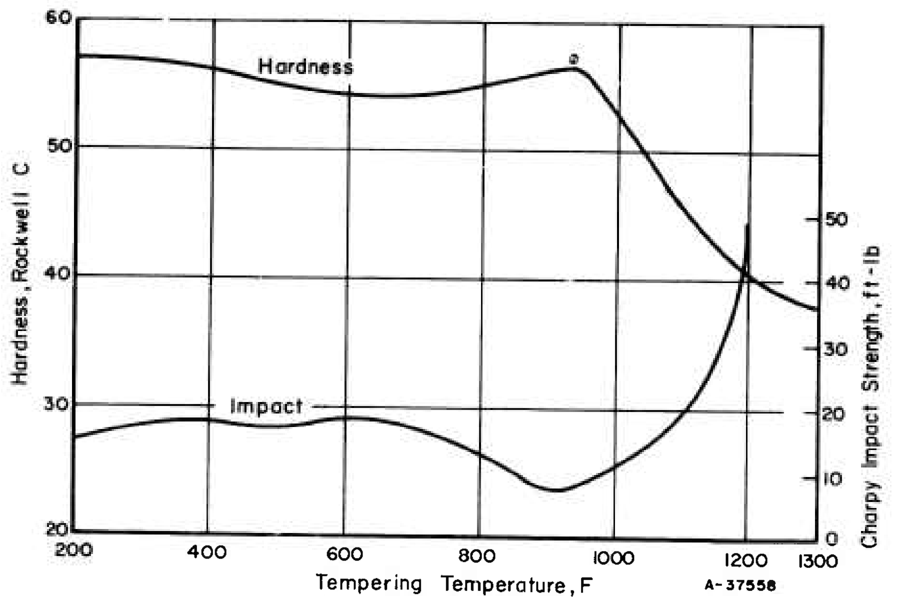

FIGURE 11. TYPICAL HARDNESS AND IMPACT VALUES OF AN H-11 STEEL AS A FUNCTION OF TEMPERING TEMPERATURE[23,24]

Because of this slow cooling, the residual stresses that would result from quenching are avoided.

The tempering characteristics of this steel (shown in Figures 10 and 11) offer particular advantages. A secondary hardening peak and minimum impact strength occur at about 900 to 950 F, as is shown in Figure 11. Therefore, tempering is conducted at still higher temperatures to obtain the best combination of strength and toughness. This high, stress-relief, temper greatly reduces all residual stresses. Any temperature above the secondary-hardness peak can be used to obtain desirable properties, and multiple tempering transforms all the retained austenite so that refrigeration treatments are not necessary. Another advantage of these steels is that they do not exhibit a "blue-brittle" tempering range such as shown around 500 to 600 F for the lower alloy steels.

Typical heat treatments for some of the steels in this class will be shown later in the section of this report on heat treatment.

DISCUSSION OF FACTORS IN THE USE OF HARDENABLE STEELS FOR SOLID-PROPELLANT ROCKET-MOTOR CASES

Although the steels used or proposed for use in solid-propellant rocket-motor cases do not behave exactly alike, they share important characteristics. Because they have many attributes in common, they can be fabricated and treated by similar methods. However, the details of the methods vary and are dependent on the special features of each steel. Some of these matters are discussed in the following sections.

Fabrication and Welding

Many rocket-motor cases are formed by the roll-and-weld technique.[6] Sheet steel is rolled into a cylinder, and the longitudinal seam is welded. The cylindrical sections then are joined to each other and to heads by welding a girth, or circumferential, seam. The heads are formed prior to welding, by machining, spinning, deep drawing, or by any of a number of other methods. Such fabrication methods require that materials for rocket-motor cases must be formable, machinable, and weldable.

The low-alloy hardenable steels can be shaped by a wide variety of methods, including machining, spinning, deep drawing, explosive forming, stretch forming, forging, and extruding.[25,26] They are formed hot or cold, depending on the forming process. In most cases, they are shaped in the soft, or annealed, condition and hardened afterward. In spinning or

drawing large components, such as heads for rocket cases, from sheet stock, the material frequently is given a special annealing treatment before being shaped. The object is to create the most favorable type of microstructure in the steel for the forming operation.

When material has been severely cold worked, or when components of substantial size or complexity of shape have been welded, cracking may occur during subsequent processing, handling, or storage. The driving force behind the cracking is a high level of internal tensile stress built up in the metal by the operations. This stress level can be reduced to safe limits by a stress-relieving thermal treatment which is carried out at low to intermediate temperatures, depending on the steel, the way the component was made, and the point in the manufacturing schedule where the stress-relief takes place. Stress-relieving temperatures for low-alloy hardenable steels range from 600 to 1200 F, the time at temperature usually being 1 to 2 hours.

The chromium hot-work die steels can be formed, drawn, and spun with little more difficulty than the more familiar low-alloy hardenable steels.[25,26] Properly annealed material and correctly spaced interstage annealing are very important with these steels. When chromium hot-work die steels are very heavily cold worked, as in severe deep-drawing operations, it is advisable to stress relieve immediately to avoid shattering on rough handling. Temperatures of the order of 750 to 925 F are frequently used for this operation. Stress relieving should be done soon after grinding, as well as prior to such operations as thread rolling, shot peening, and plating. The process, or interstage, anneal may be carried out at 1450 F followed by air cooling. An illustrative full-annealing schedule comprises preheating to 1200 F, raising the temperature to 1650 F, and furnace cooling to 850 F followed by air cooling to room temperature.

The parts should be thoroughly cleaned and free from rust, scale, or oil before heat treatment. Cleaning and descaling are preferably done by mechanical means, such as sand, grit, or vapor blasting. Scale also may be removed by anodic pickling. If the latter procedure is used, the current should be on prior to and all during the immersion of the work in the electrolyte. Acid pickling and cathodic pickling invite embrittlement from absorption of hydrogen, and should be avoided.

The two welding processes that are used more widely than any others for solid-propellant rocket-motor case fabrication are the inert-gas tungsten-arc process and the submerged-arc process. The submerged-arc process has the following limitations as compared with the inert-gas tungsten-arc process: (1) chemical composition is more difficult to control; (2) the minimum plate thickness that can be welded with reasonable success is about 1/8 inch; and (3) the lack of visibility of the submerged-arc process makes it mandatory that weld-seal tracking be good.[6] The

submerged-arc process does achieve higher production rates. Filler wire of the same composition as the base metal is commonly used in either welding process. Joints must be preheated and postheated carefully to prevent cracking, and frequently they are not permitted to cool until after stress relief so as to reduce weld-metal cracking under high restraint. Filler wire of low sulfur and phosphorus contents is recommended.

Preheat and postheat are used for two reasons — to help reduce or prevent weld-metal cracking and to produce an as-deposited weld-metal microstructure of maximum ductility for ease of handling. Most rocket-motor-case welding fixtures are fitted with heaters to provide the preheat and postheat. For this reason, the postheat is usually the same temperature as the preheat. There is wide disagreement over the optimum preheat and postheat temperatures for welding the various steels used for cases. In general, the lowest preheat and postheat temperatures that can be used satisfactorily to produce a structure of maximum ductility are employed.

The successful fabrication of rocket-motor cases is an exacting operation. Techniques commonly used to produce plain-carbon steel pressure vessels are not satisfactory for rocket fabrication. Overlooking a seemingly minor detail can result in failure during hydrostatic testing, as past experience has shown.

Heat Treating

The principal reason for using high-strength steels is to minimize the weight of a rocket-motor case. It is for this reason that the cases are heat treated to high-strength levels. However, if the surface of the steel has been decarburized, the entire cross section will not be at full strength; the surface layer will be weakened. Although decarburization generally is considered detrimental, some fabricators advocate a small, controlled amount of surface decarburization to reduce sensitivity to surface flaws. The production of a small, controlled amount of decarburization in a component, however, is a difficult matter.

Decarburization may be produced during hot rolling in the mill or during heat treatment after fabrication. Mill decarburization either can be removed by grinding or chemical milling or it can be prevented by sandwich rolling. Sandwich rolling has the additional advantage of reducing the sheet-thickness tolerances required by steel mills.

Decarburization and scaling, as well as carburization, may be encountered during hardening, annealing, and normalizing heat treatments. Any of these effects is usually undesirable, particularly when the heat-treated component is not given any further machining or finishing. Controlled furnace atmospheres, molten neutral salt baths, and protective

coatings (usually proprietary compounds) are used to prevent or minimize these problems.

Two commonly used protective atmospheres are those referred to as "endothermic" and "exothermic". Following is an example of an endothermic atmosphere produced by burning a 2.25:1 air:fuel gas mixture in the presence of a catalyst and an illustrative exothermic atmosphere that results from burning a 9.5:1 air:fuel gas mixture:

Atmosphere	Composition, per cent CO	H_2	CH_4	N_2	Dew Point, F
Endothermic	19.0	38.0	1.5	41.5	-10
Exothermic	2.0	2.0	--	96.0	-40

External heat must be applied in burning an endothermic mixture, while none is needed for an exothermic atmosphere.

The capability of such atmospheres to carburize or to decarburize is strongly influenced by the presence of small amounts of water vapor. Therefore, control of the dew point of the furnace atmosphere affords a convenient means of regulating the degree of neutrality of the atmosphere toward the work. As a check on this, it is common to include a separate decarburization sample in each load being heat treated. The composition of the atmosphere and the steel, as well as the heat-treating temperature, determines the dew point at which neutrality prevails.

Neutral salt baths are usually molten mixtures of chlorides or of chlorides and carbonates to which a "rectifier" such as methane, graphite, or ferrosilicon is added to keep the bath neutral toward the work.

Illustrative heat treatments for some of the low-alloy hardenable steels and some of the hot-work die steels are listed in Table 5.[5,27] The heat-treating practices used by the different missile manufacturers vary considerably. Such dissimilarities seem to stem largely from individual needs. Therefore, the information in Table 5 is only of a general nature and cannot be considered as a list of heat-treating rules. Although the austenitizing temperatures listed in Table 5 cannot be considered exact, they do illustrate a general principle, namely, as the amount of carbide-forming alloying elements is increased, it is necessary to increase the austenitizing temperature to dissolve the carbides formed. If the alloy carbides are not dissolved, the alloying elements will not fulfill their intended functions properly, and the results of the heat treatment will be different from what was anticipated. In particular, the hardenability and secondary hardening effects will be impaired. Also, if too much carbon remains undissolved in the austenite, it may not be possible to achieve the desired strength, because the carbon content of the martensite will be lower than was intended.

TABLE 5. ILLUSTRATIVE HEAT TREATMENTS FOR SOME LOW-ALLOY HARDENABLE STEELS AND 5Cr-Mo-V HOT-WORK DIE STEELS[5, 27]

Steel	Annealing	Normalizing	Hardening: Austenitizing Temperature, F	Hardening: Quench	Tempering[(a)]: Temperature, F	Tempering[(a)]: Time, hr
AISI 4130	1525-1575 F, furnace cool	1600-1700 F, air cool, stress relieve at 900 F	1550-1600 1575-1625	Water Oil	400	--
AISI 4140	1550 F, furnace cool to 900 F, then air cool	1650 F	1575	Oil	1200	--
17-22-AS	1750 F, furnace cool to 1325 F, hold 4 hr, air cool	--	1750	Oil	1000	--
UCX-2 (MX-2)	--	1750 F, draw at 1250 F for 2-hr minimum	1725	Oil	550 (double temper)	2
MBMC No. 1	1300-1350 F for 40 hr, furnace cool to 1000 F, air cool	1600 F, draw at 1325 F for 2-hr minimum	1575	Oil or salt	575	1
Airsteel X-200	1330-1380 F for 40 hr, furnace cool to 1000 F, air cool	1750 F, draw at 1350 F for 2-hr minimum	1725	Oil or salt	700	1/2 min
AISI 4340	1550-1650 F, furnace cool to 900 F, air cool	1650 F, air cool or furnace cool to 1275 F and air cool	1525-1575	Oil	450	--
AMS 6434	1650 F, furnace cool to 600 F, air cool	1650 F, air cool	1650	Oil	400	--
D-6-AC	1350 F for 40 hr, furnace cool to 1000 F, air cool	1600 F, draw 2-hr minimum	1550	Air cool	600	4

TABLE 5. (Continued)

Steel	Annealing	Normalizing	Hardening: Austenitizing Temperature, F	Hardening: Quench	Tempering[a]: Temperature, F	Tempering[a]: Time, hr
300-M (Tricent)	1430 F, slow cool to 900 F, air cool	1700 F, air cool	1600	Oil	500-600 (double temper advised)	--
HY-Tuf	1600 F, air cool, reheat to 1200 F for 16 hr, air cool	--	1600	Oil	400-600 (550 preferred)	--
USS Strux	1500 F, furnace cool	1600-1650 F, air cool	1550	Oil	450-550	--
5Cr-Mo-V Aircraft	1550-1650 F, slow cool to 1000 F, air cool	--	Preheat 1200-1300, 1850	Air cool	1000-1075 (double or triple temper)	--
Vascojet 1000	1500-1550 F, slow cool to 1000 F, air cool	--	Preheat 1000, 1800-1900	Air cool	1000-1200 (double temper)	--
Crucible 56	--	--	Preheat 1400, 1950	Air cool	Double temper	--
Crucible 218	--	--	Preheat 1200, 1800	Air cool	975-1050 (double temper)	--
Potomac A	--	--	Preheat 1500, 1900	Air cool	1000 (double temper)	--
Potomac M	--	--	Preheat 1500, 1900	Air cool	1000 (double temper)	--
Unimach II	1575 F, furnace cool to 800 F, air cool	--	Preheat 1200, 1800-1850	Air cool	1000 (double temper)	--

(a) All steels double or triple tempered depending upon the final application.

Multiple tempering is a common practice for rocket and missile steels. The second or third tempering treatment provides additional stress relief and tempers any martensite that may have formed from retained austenite during the first temper. All alloy steels contain some retained austenite after quenching.

Although the low-alloy hardenable steels possess sufficient over-all hardenability so that sheet material will be fully hardened on air cooling, they are usually quenched. The requirements for uniformity in rocket-motor cases are so exacting that any small localized variation in hardenability due to heterogeneity of the steel which might result in anything other than a fully hardened structure on air cooling could not be tolerated. The distortion resulting from quenching stresses can be minimized by a stress-relieving treatment prior to hardening and by quenching into molten salt or hot oil if the steel possesses sufficient hardenability. The hot-work die steels have sufficient excess hardenability due to their high content of alloying elements that air hardening is feasible for sheet material. Any heterogeneities due to ordinary steelmaking practices would not be sufficient to result in any transformation products other than martensite.

Some of the missiles have become so large and the dimensional tolerances so exacting that small distortions resulting from welding and heat treatment cannot be tolerated. Therefore, the parts usually are welded and heat treated in the same jigs. Another problem presented by the size of missile components is the need for special heat-treating equipment that can be closely controlled in spite of the large size. Large bottom-opening, gantry furnaces, which heat treat the parts in a vertical position to help prevent distortion, have been developed to fulfill this need.[28]

Short-Time Elevated-Temperature Properties

Missile development is placing ever-increasing temperature demands on structural steels. Service temperatures ranging from 800 to 1000 F appear probable.[21] Flat-rolled materials for airframe and missile applications should have moderate corrosion resistance and short-time, elevated-temperature mechanical properties approximating the values given below:[22]

Service Temperature	Minimum Tensile Strength, psi
Room	260,000
800 F	200,000
1000 F	170,000
1100 or 1200 F	120,000

The short-time elevated-temperature properties of low-alloy hardenable steels and hot-work die steels are compared in Figure 12. This figure shows the superiority of the hot-work die steels for such use. The possible disadvantage to the use of hot-work die steels is that, like the low-alloy hardenable steels, they have poor corrosion resistance. Some experiments have been conducted with hot-work die steels clad with stainless steel which show that the clad steel meets the tensile-strength requirements for service at 1000 F. However, the elongation values of the clad sheet were low.

A comparison of the properties of hot-work die steels with stainless steel for short-time, high-temperature service up to 1000 F indicates that the hot-work die steels achieve a higher level of tensile and yield strength over the entire temperature range and have the same elongation values as do the stainless steels. Among the various classes of steels considered for this service, the hot-work die steels offer highest tensile strengths and strength-to-weight ratios up to 1000 F, based on short-time tensile tests. Though most parts would require coatings or cladding for corrosion protection, the hot-work die steels of the H-11 type should find high-temperature application for aircraft and missiles.

Notch Sensitivity

Perhaps one of the most important considerations in rocket-motor material evaluation is notch sensitivity. High-strength steels heat treated to their highest strengths will have low tolerance for even very small flaws.(29) On the other hand, a steel heat treated to a lower tensile strength (a more ductile condition) will be more tolerant to flaws, and the material will be stronger in the presence of notches or flaws. This general trend is shown schematically in Figure 13, in which the tensile strength of notched specimens with different stress-concentration factors, K, (or different degrees of notch acuity) is shown as a function of strength level (determined for unnotched specimens). The introduction of a notch into a tensile specimen develops multiaxial tensile stresses which may result in an apparent strength increase, if the strength of the unnotched specimen is relatively low. This is depicted in the lower left region of Figure 13, where the notched strength exceeds the unnotched strength. For a low strength level, S1, no notch sensitivity is displayed for any value of K. At a somewhat higher level of strength, S2, the material is notch sensitive when the stress-concentration factor is high, but not when it is low. When the strength level equals S3, notch sensitivity is manifested even for relatively low stress-concentration factors.

Conventional tensile tests of high-strength steels do not provide sufficient information to predict performance of complex structures fabricated from such materials. The best test to simulate the actual conditions in the solid-propellant rocket-motor case is a rocket motor. No exact method is

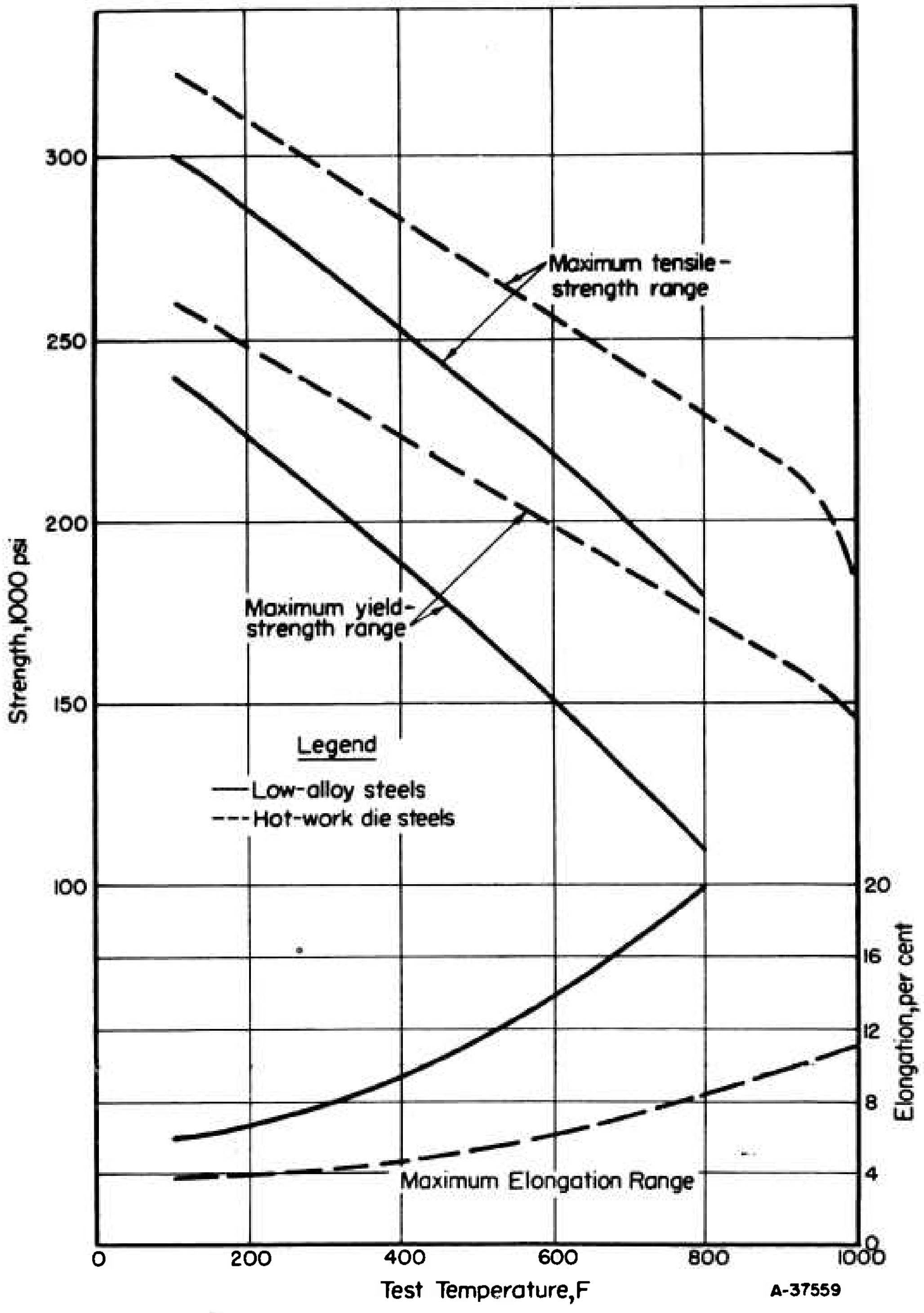

FIGURE 12. TYPICAL MAXIMUM SHORT-TIME, ELEVATED-TEMPERATURE PROPERTIES OF LOW-ALLOY STEELS AND HOT-WORK DIE STEELS[25]

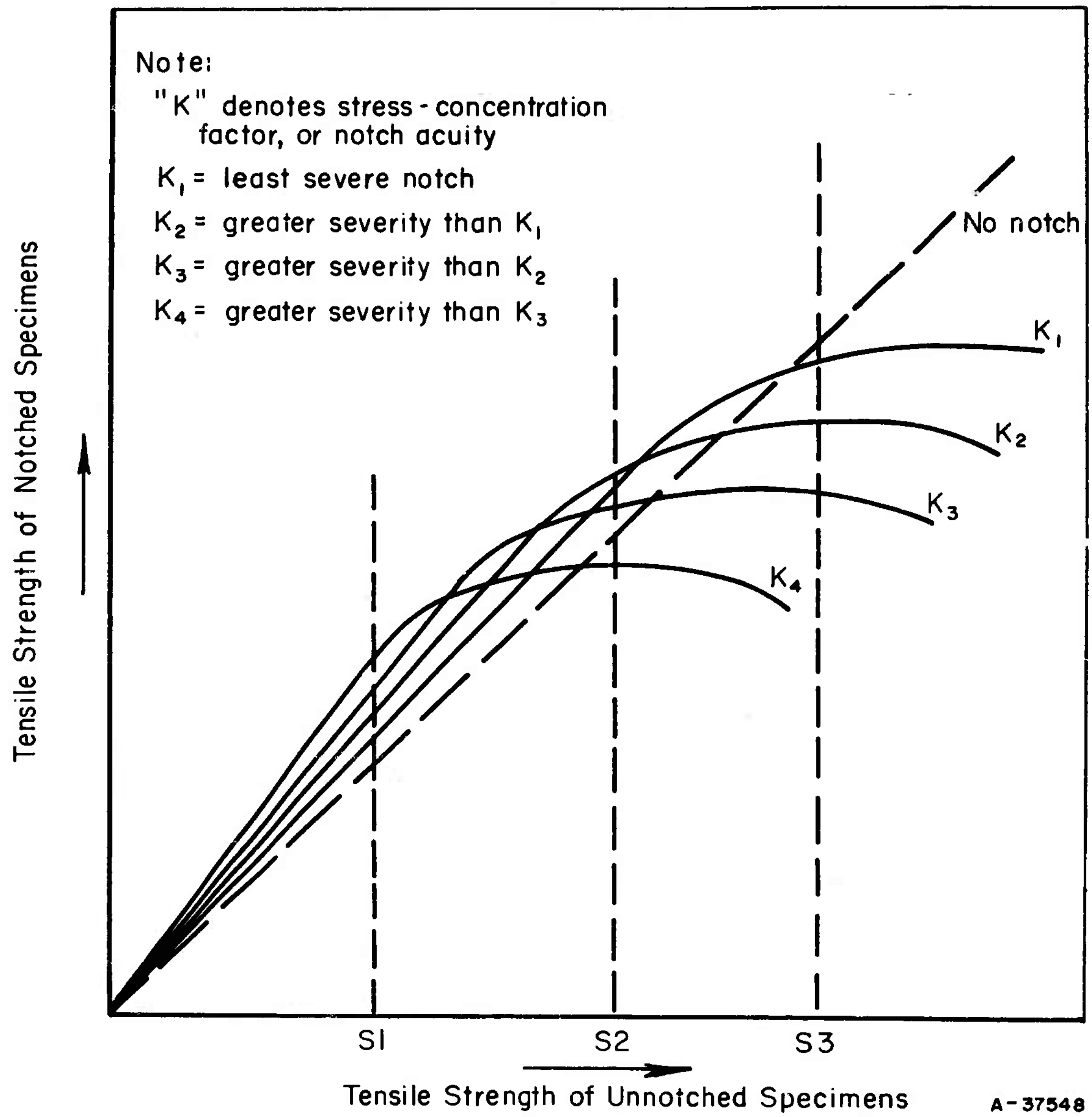

FIGURE 13. SCHEMATIC REPRESENTATION OF THE EFFECT OF STRENGTH LEVEL AND STRESS-CONCENTRATION FACTOR ON THE TENSILE STRENGTH OF NOTCHED SPECIMENS

known to duplicate these service conditions. However, approximations to the behavior of materials in motor-case applications can be arrived at in the laboratory under less complex conditions.[30,31] Flaws, stress concentrations, cracks, and service stresses are not constant from one rocket-motor case to the next. Consequently, approximations to behavior are all that can be expected from any laboratory test.

Tests applied to materials frequently are divided into two categories: (1) tests to determine useful strength values and design criteria, and (2) screening tests to evaluate materials. Screening tests, or tests for evaluation of materials, generally are simpler than tests to establish design allowables. An example of a screening test for materials for rocket-motor-case applications is a tensile test using a specimen containing a sharp, controlled notch. This test differentiates between materials of differing notch sensitivity, but does not yield values directly applicable to design. The more promising materials and treatments shown by screening tests may then be subjected to more complex methods of evaluation.

No one screening test has been universally accepted. Each proponent of a particular test has certain specific reasons for preferring that test over others. Other screening tests in addition to the sharp-notch tensile test, or the center-crack tensile test, are: unnotched-bend, bulge, tear, and notched-impact tests. Details of most of the tests, including specimen preparation and typical results, may be found in Reference (32).

Hydrogen Embrittlement

The low-alloy hardenable steels and the 5Cr-Mo-V (hot-work die steels) all are susceptible to hydrogen embrittlement. Therefore, any operation which invites hydrogen pickup, such as acid pickling, cathodic pickling, or electroplating, should be avoided if possible.

Recently, a few failures of rocket cases during hydrostatic testing have been attributed to hydrogen-induced delayed failure, resulting from hydrogen pickup during the tests.[33] Small pits acting as anodes could cause hydrogen to be released from the testing liquid, and it could diffuse into the steel in areas of high current density (cathodic areas) near the pits. Thus, though the general level of hydrogen might be low, the level in the vicinity of the pit might be high. Under stress and in the presence of a stress concentration (such as a pit or notch), the hydrogen would diffuse to the point of maximum triaxiality.[34] For sharp notches, the point of maximum triaxiality lies close to the surface near the root of the notch, while for rounded notches it lies at some distance below the surface. The combination of hydrogen release by galvanic action and the stress-concentration effect of the pit could result in the initiation of a very small crack. With continued testing, the crack could grow until it reached sufficient length to cause catastrophic failure.

Thus, the hydrogen-induced failure of rocket-motor cases should be considered as a possibility in analyzing failures which occur during hydrostatic testing.

Ausforming as a Method of Increasing Strength

Ausforming is a possible method for increasing the strength of ultrahigh-strength steels. In the laboratory, this process has produced steels with yield strengths of the order of 400,000 psi. The process consists of heating the steel to austenitize it, then plastically deforming the steel at a temperature at which the austenite is metastable, and then allowing the steel to cool. This operation is followed by tempering. Ausforming of sheet material is still in the development stage. Austenrolling and interrupted-quench mechanical working are other names for this process. So far, the results of various investigations have not been entirely consistent, nor has there been evidence that the process is sufficiently reproducible to be used on a production basis.

The following observations have been made in the brief period that ausforming has been under systematic investigation.[35] Strength levels are generally a function of the percentage of deformation, the temperature of deformation, and the degree of subsequent tempering. A critical degree of deformation is required before any significant increase in strength is obtained; after this level is reached, strengths increase uniformly with increasing amounts of deformation. With high degrees of deformation, the yield and ultimate strengths become approximately equal.

The temperature of deformation is critical because neither recrystallization nor transformation should take place during the deformation process; if either occurs, the strength of the resulting material will be low. To prevent the temperature of the piece from being raised to the recrystallization temperature, it is necessary to avoid high rates of deformation and to control the temperature of the piece accurately before and during the reduction. Some investigators have observed recrystallization to occur with little or no increase in temperature after reduction has exceeded 50 per cent. Deformation at 1000 F increases both the yield strength and the tensile strength, whereas deformation at 1550 F increases the yield strength but has little effect on the tensile strength.

In general, the greatest strengths of ausformed steels have been achieved with high carbon contents and maximum deformations. A steel that contained 0.63 per cent carbon and which was deformed 90 per cent had an ultimate strength of over 465,000 psi, with 8 per cent uniform elongation, in the untempered state.

The basic mechanism responsible for these ultrahigh strengths is not known, nor is it known what transformation products form when the

deformed austenite transforms on cooling. If current investigations into the ausforming process disclose the mechanism involved and make it possible to reproduce, on a production basis, strengths frequently achieved in the laboratory, this process may become quite useful.

Vacuum Melting

Vacuum melting has produced marked improvements in the cleanliness of steel, and this in turn has resulted in improvements in the transverse properties, particularly the endurance limit and ductility of the steel. In many instances the properties in the transverse direction approach those in the longitudinal direction. The ultimate and yield strengths of steel are not improved by vacuum melting. Although vacuum melting adds significantly to the cost, many missile manufacturers believe that the benefits justify consideration of vacuum-melted steels for missile application. Table 6 contains a summary of the benefits to be expected.

As shown in Table 6, the two large-scale vacuum-melting methods are vacuum-induction melting and consumable-electrode-arc remelting. Duplexing the two methods, vacuum-induction melting followed by consumable-electrode remelting, showed the greatest improvement in properties.

Another vacuum process for improving the quality of steel involves pouring the molten metal through a vacuum. Although vacuum pouring does not result in the high degree of refinement obtained with vacuum melting, it does remove large quantities of gaseous impurities from the metal, and the hydrogen content of steels can be reduced significantly by this method.

There are several variations of vacuum pouring or degassing. Molten metal can be poured from one ladle through a vacuum into another ladle or directly into the mold. Another method of degassing is to place the entire ladle of molten metal in a vacuum chamber and then to cast in the vacuum after allowing a period of time for degassing.

All the types of steel discussed in this report have been produced experimentally, or are now being produced commercially, by vacuum melting.

TABLE 6. A SUMMARY OF THE CHARACTERISTICS OF AIR-MELTED AND VACUUM-MELTED ALLOYS (36)

Melting Method	Melting Variables: Temperature, F	Melting Variables: Pressure	Melting Variables: Time Metal Molten	Product Characteristics: Hot Workability	Product Characteristics: Gas Content, ppm	Product Characteristics: Cleanliness	Product Characteristics: Segregation	Product Characteristics: Properties
Air	2500 to 3100	1 atm	2 hr to 3 hr	Poor to fair	H 4-20 O 10-150 N 30-500	Fair	Normal	Normal
Vacuum-induction	2500 to 3100	1 to 100 microns	1 hr to 5 hr	Good	H <1 O 4-10 N 3-50	Very clean	Normal	Improved by 20 to 200 per cent
Consumable-electrode vacuum-arc remelting								
From air-melted electrode	2500 to 8500	5 to 500 microns	15 to 30 minutes	Good	H 1-2 O 6-30 N 30-100	Clean	Relatively free	Improved by 10 to 100 per cent
From vacuum-induction-melted electrode	Ditto	Ditto	Ditto	Very good	H <1 O 1-5 N 2-20	Extremely clean	Ditto	Improved by 30 to 300 per cent

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